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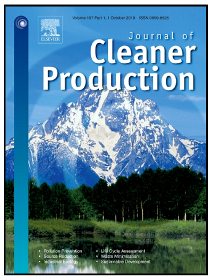

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PII:	S0959-6526(18)32386-2
DOI:	10.1016/j.jclepro.2018.08.052
Reference:	JCLP 13836
To appear in:	*Journal of Cleaner Production*
Received Date:	14 September 2017
Accepted Date:	05 August 2018

Please cite this article as: Farzad Piadeh, Mohsen Ahmadi, Kourosh Behzadian, Reliability Assessment for Hybrid Systems of Advanced Treatment Units of Industrial Wastewater Reuse Using Combined Event Tree and Fuzzy Fault Tree Analyses, *Journal of Cleaner Production* (2018), doi: 10.1016/j.jclepro.2018.08.052

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Reliability Assessment for Hybrid Systems of Advanced Treatment Units of Industrial Wastewater Reuse Using Combined Event Tree and Fuzzy Fault Tree Analyses

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Abstract

Advanced treatment units (ATUs) are highly recommended for industrial wastewater reuse in the developing countries especially in arid and semi-arid areas. Reliability of a hybrid treatment system comprised of a number of individual ATUs remains blur due to lack of conceptual framework, collected data or experience in failure performance analysis of these treatment systems. This paper presents a new methodological framework for assessing reliability of hybrid system alternatives in industrial wastewater treatment by using combined event tree analysis (ETA) and fault tree analysis (FTA). The framework comprises three major steps: (1) identification of feasible alternatives; (2) reliability analysis assessment using combined FTA and ETA with fuzzy logic techniques to calculate first failure probability of individual ATUs and then reliability of each hybrid system alternative; (3) prioritisation of alternatives. Failure probability rate of events in FTA is determined by experts' judgement. The suggested framework is demonstrated through its application to a real case study of wastewater treatment plants of industrial parks in Iran. The results show the highest failure probabilities are reverse osmosis unit with 30% and ozonation unit with 24%, while coagulation and flotation unit has the lowest failure probability of 5.4%. The most reliable alternative of hybrid system is comprised of sand filter + activated carbon + micro filter + ultra-filter + ion exchange with 74.82% reliability. Results in this study also show that selecting ATUs with higher removal efficiencies or rate of acceptable scenarios to form a hybrid ATU system cannot necessarily lead to a more reliable hybrid system without performing suggested FTA and ETA in this paper.

Keywords: Advanced Treatment Units, Event tree analysis, Fault tree analysis, Fuzzy logic, Hybrid systems of industrial wastewater, Reliability.

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1 Introduction

Nowadays, advanced treatment units (ATUs) are widely used for industrial wastewater treatment in order to not only prevent discharging contaminated wastewater to receiving water bodies but also provide opportunities for non-conventional water resources (Mya and Groth, 2011; Zhu *et al.*, 2015). This new way of cleaner production particularly is of paramount importance to developing countries especially located in arid and semi-arid areas usually suffering from lack of sufficient fresh water. Selection of the best sustainable combination of ATUs in series as a hybrid system in industrial wastewater treatment plant (WWTP) can sometimes turn out to be a serious challenge due mainly to uncertainties available in the operation of ATUs (Piadeh et al., 2014). This can be even more challenging in developing countries where the sustainable performance of ATUs cannot be easily determined due to some major reasons including (1) different purposes for treatment of a hybrid ATU system and lack of collected data or required experience and knowledge for operation of such systems (Chong, 2012), (2) inability to recognise vulnerable points for a hybrid system in operation (Silva, 2014), and (3) major concerns about failure of such systems during the operational phase (Kalbar, 2012). Thus, an assessment framework for analysis of the performance of these systems is highly recommended.

Many researches have proposed set of indices for sustainability performance assessment of hybrid ATU systems (Piadeh *et al.,* 2018; Castillo *et al.*, 2017; Mahjouri *et al.* 2017). Among all, reliability can be understood as one of the main criteria in assessment methods for analyse of the sustainability performance in hybrid ATU systems during the operational phase (Zhang *et al.*, 2012; Chong *et al.*, 2012). Improvement of operational reliability in hybrid systems can also have a direct impact on minimisation of future failures related to undesirable operation and hence indirectly influence other criteria such as economic (e.g. repair costs), technical (e.g. delivery of desirable removal efficiency and social (e.g. stakeholder satisfactory) aspects.

The first attempts about reliability assessment of wastewater treatment were made around the late 20th century and related to fault diagnostic or fault tree analysis (Harris, 1985). Fault tree and event tree analyses were employed widely for assessment of failure, risk or reliability in different industries such as oil and gas transmission pipelines (Yuhua and Datao, 2005), highway tunnels (Nývlt *et al.*, 2011) and nuclear power plants (Purba, 2014). Although these analyses have also been used in water and wastewater treatment, their applications have been limited to some specific

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applications and definitions. Metcalf & Eddy (2003) defines reliability in water and wastewater industry as the possibility of obtaining expected adequate effluent quality in a specific period under certain conditions. Fault tree analysis is used more frequently for water distribution networks (Gouri and Srinivas, 2015; Gutpa and Rathi, 2017).

Some recent applications and definitions of reliability assessment in wastewater treatment systems are summarised in Table 1. The reliability assessments with qualitative methods in the Table were all provided by expert opinions without quantitative methods. This assessment method cannot be simply applied for other areas especially developing countries where enough experience is unavailable for running advanced treatment units. The other method, i.e. percentage of desirable effluent quality, is strictly dependent on the ability of treatment system to provide the required water or treated wastewater regardless the probability of unit's working. The last method, coefficient of reliability as a quantitative method, needs a large volume of precise historical data. However, this is the main obstacle for the cases when no or little historic data are available. Hence, an appropriate method is required for quantification of failure probability rates of ATUs for the cases with no historical data or poor quality of available data. Despite many failure probability assessments in different industries including wastewater treatment industry, they have been applied for a single processing unit not for combined failure assessment of a number of units in series as hybrid systems. In particular, some research works considered a correlation between the removal efficiency and reliability and hence ranked the reliability of alternatives based on their ability for removing pollutants (Arroyo and Molinos-Senante. 2018; Di Iaconi *et al.*, 2017). These studies assume that the treatment system works all times with maximum efficiency without failure during their life-cycle (Oliveira and Von Sperling, 2008; Alderson *et al.*, 2015). In addition, designers usually prefer to select ATUs in a hybrid system of wastewater treatment based on two approaches (ISIPO, 2016): (1) selecting ATUs with higher removal efficiency ; (2) selecting ATUs with larger reliability. However, both approaches fail to consider the effects of faulty ATUs in a hybrid system and hence the overall reliability of the hybrid system cannot be analysed properly.

Table 1 Recent applications and definitions of reliability assessment in wastewater treatment systems

Treatment processes	Reliability definition	Assessment method	Reference
166 full-scale wastewater treatment plants with 2 or 3 hybrid units	Probability of achieving adequate performance for a specific period of time under specific conditions	Coefficient of reliability	Oliveira and Von Sperling, 2008
EA[1], AB[2], IFAS[3], SBR[4], AL[5]	Long-term reliability of the processes	Qualitative	Karimi *et al.*, 2011
AS[6], SBR, MBR[7]	Probability of mechanical failures and the impact of failures upon effluent quality for variability of treatment effectiveness under normal and emergency operation	Qualitative	Kablbar *et al.,* 2012
CW[8], PS[9], EA, MBR, RBC[10], TF[11], SBR	As above	Qualitative	Molinos-Senante *et al.,* 2014
56 wastewater treatment plant with hybrid systems	Reaching removal efficiency with desired national standard	Coefficient of reliability	Alderson *et al.,* 2015
CW	Reaching acceptable removal efficiency	Percentage of removal efficiency	Wojciechowska *et al*., 2016
CW	Reaching acceptable removal efficiency	Percentage of removal efficiency	Jó źwiakowski *et al*., 2017
SBBGR[12]	Reaching acceptable removal efficiency	Qualitative	Di Iaconi *et al*., 2017
General wastewater treatment systems	Reaching required level of treatment, or system shutdown due to hardware or process problem, or enduring shock load due to the influent characteristics variation, or system performance in face of weather variation	Qualitative	Mahjouri *et al*., 2017
20 hybrid systems	Mechanical reliability and water quality reliability	Qualitative	Akhoundi and Nazif, 2018
CW	Ability to remove amount of pollutants	Weibull analysis	Jóźwiakowski *et al*., 2018
TF, SBR, RBC, PS, MBR, CW	Reaching the removal efficiency to the desired standard	Qualitative	Arroyo and Molinos-Senante., 2018
8 hybrid systems	Excessive loads of hydraulic, organic (COD), TSS or corrosions	Qualitative	Piadeh *et al*., 2018

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Most of the research works as described in Table 1 has focused on reliability assessments of secondary treatment units such as either individual units (e.g. SBR, IFAS and CW) or hybrid systems, which used for meeting the standards to improve the quality of wastewater for cosumers who do not need high quality water. However, advanced treatment units are necessary in order to completely treat the wastewater as a new water resource instead of fresh industrial water. Only few analysed reliability assessment for some specific advanced treatment units. More specifically, Kalbar *et al.* (2012) that investigated a hybrid system containing three MBR units assumed MBR has the highest reliability rate (i.e. 100%) while the reliability of MBR systems was reported moderate (50%) by Molinos-Senante et al. (2014) and 30% by Arroyo and Molinos-Senante (2018). This highly variable rate for reliability of MBR systems shows various conditions and technological manufacturing of MBR systems that led to a large range between experts. Despite several recent advances in the development of reliability-based assessments in industrial WWTPs, to the best of author's knowledge, none of the previous works has presented a quantitative method to measure and compare the reliability of ATUs and more importantly investigate the reliability of hybrid ATU systems comprised of a number of individual ATUs in industrial wastewater treatment. Hence, this paper aims to develop a methodology for reliability assessment of hybrid ATU systems of industrial treatment by using an analytical method comprised of event tree and fault tree analyses. The paper also aims to integrate event tree and fault tree analyses into fuzzy logic and experts' opinions to quantify the failure data used for reliability assessment of hybrid ATU. This can lead to determine failure probability of individual ATUs and then reliability of hybrid systems. This method can be used to identify appropriate hybrid system alternatives for industrial treatment. Next section describes the suggested methodology followed by illustrating feasible alternatives, acceptable state and event tree and fault tree in a real case study. The results are then discussed and key findings are finally summarised along with future works.

2 Materials and methods

2.1 Framework of reliability assessment

A new framework for reliability assessment of the advanced treatment of industrial wastewater is described here, which uses a combined analytical methodology consisting of event tree, fault tree and fuzzy logic theory. Here, it is assumed that this methodology is used for industrial

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advanced wastewater treatment systems which followed by other treatment process. In this situation, entered wastewater/influent into ATUs is previously treated by secondary treatment processes.

Generally, the framework as shown in Fig. 1 comprises three major steps of inputs, reliability assessment and outputs. The first step entails identifying alternatives of hybrid ATU systems and specifying assessment criteria in accordance with rational options and national regulations/targets. The data required in this step are collected based on the documents related to historic performance of advanced wastewater treatment provided by stakeholders and/or available in the literature. A single alternative is defined here as a combination of multiple units in advanced treatment (Fig. 2) which can provide treated wastewater in accordance with desirable water quality for industrial reuse purposes (e.g. boilers and cooling towers in factories).

The second step consists of reliability assessment of each alternative using a combination of fault tree and event tree analyses. More specifically, the event tree first provides a list of all possible scenarios of performance for each alternative based on different combinations of success and failure states of each ATU in the alternative. For each alternative, event tree analysis then identifies "acceptable scenarios" which is defined for a scenario when the water quality of the treated effluent in the hybrid ATU systems is within standard limits based on the assessment criteria defined in Step 1.

The fault tree analysis is then applied to specify the failure probability of each ATU individually by using fuzzy logic technique and experts' judgement. This can be used to calculate the failure probability of all ATUs in each alternative and after defuzzification of failure probability, crisp number can be used to calculate the failure probability of each scenario in event tree analysis. Details of the terms, methods and assumptions used in each step are further described in the following subsections.

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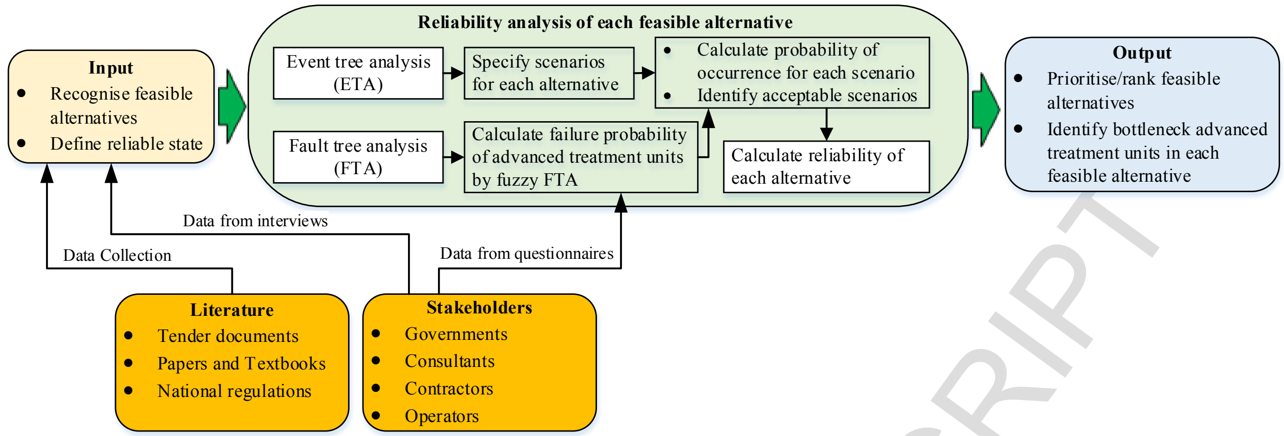

Fig. 1 Suggested framework for the reliability assessment of ATUs

2.2 *Feasible alternatives*

Numbers of feasible alternatives are specified here for reliability assessment. Each alternative is a combination of *n* advanced treatment units as shown in Fig. 2. Feasible alternatives of industrial wastewater treatment can generally be introduced based on the scale used for treatment such as individual, decentralised, cluster, satellite and centralised systems. Centralised WWTP is more recommended for industrial wastewater in developing countries compared to other scales due to their advantages in some criteria such as economic and ease of management (Piadeh *et al*, 2014; Üstün *et al.*, 2011). Centralised WWTP generally includes primary and secondary treatment, which can provide treated wastewater for non-potable water reuse without a high-quality standard. However, advanced treatment is necessary in order to provide treated wastewater for discharge into receiving water bodies.

Two general approaches can be considered for advanced treatment of the secondary effluent. The first approach adopts the treatment of the entire secondary effluent but it may need a large capital investment. This seems to be a less attractive option for developing countries that may suffer from lack of sufficient economic resources (Adewumi *et al.*, 2010). Alternatively, the second approach considers a blending system (Piadeh *et al.*, 2014) in which only a small proportion of the secondary effluent is first treated by ATUs and then is blended with the remained secondary effluent (Fig. 2). The industrial wastewater treatment analysed here is following the second

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approach, i.e. the treated wastewater discharged into receiving water is a combination of secondary and advanced treated effluent.

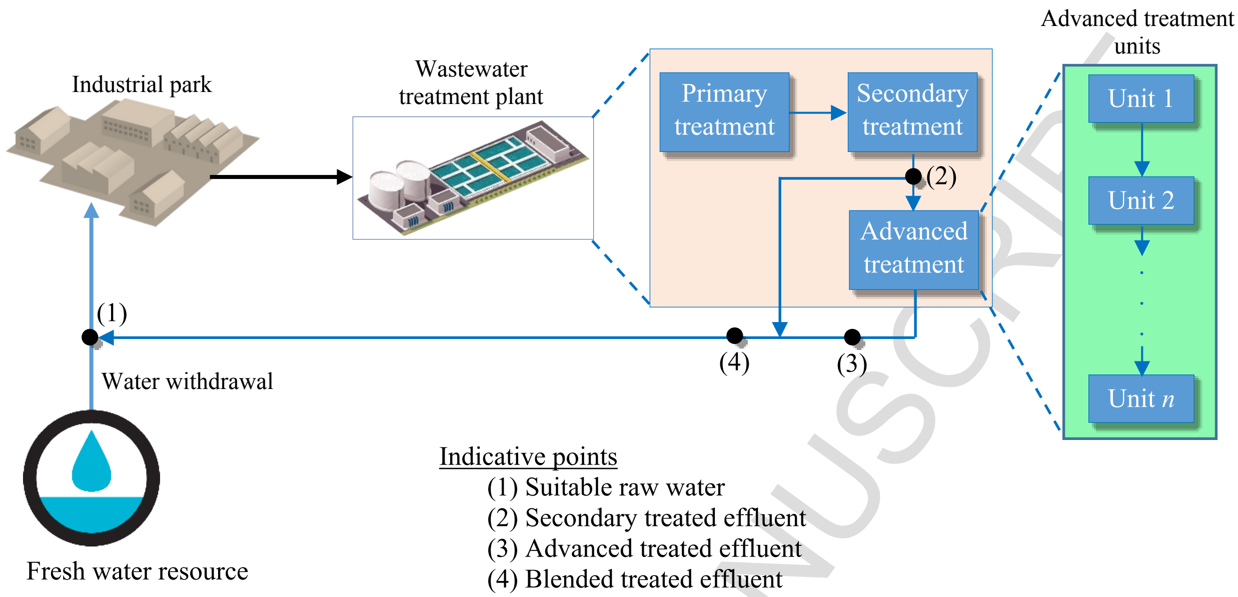
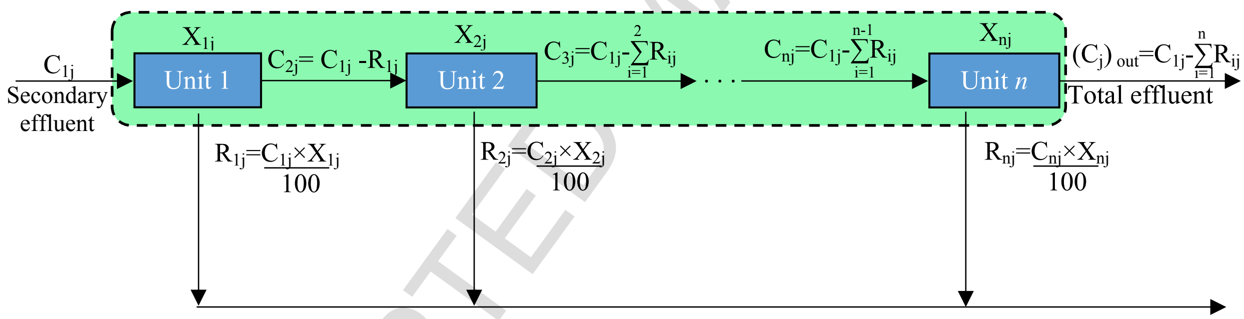


Fig. 2 Schematic flow-diagram of a typical industrial wastewater treatment

2.3 Acceptable state analysis

Based on the success or failure function of each ATU, the performance of a feasible alternative can be evaluated in different scenarios based on the water quality of the treated effluent. Hence, the performance of a feasible alternative with a series of ATUs is called acceptable if the treated effluent (i.e. point 4 in Fig. 2) is within standard limits of water quality under specified conditions during a given period (Bourouni, 2013). The assessment requires that for each of the *n* units in an alternative, a specific removal efficiency for each pollutant is first specified. For example, in the series of *n* units shown in Fig. 3, Unit 1 receives the secondary effluent with pollutant concentration *j* (C_{1j}) and reduces the concentration by specific removal efficiency (X_{1j}) and finally discharge the treated effluent with pollutant concentration *j* (C_{2j}) which is the input of the following unit. As such, the treatment by-product with pollutant concentration *j* (R_{1j}) is also extracted from Unit 1. The treatment process continues sequentially until the last unit (Unit *n*) in which the advanced treated effluent is blended with secondary treated effluent to account for the overall blended effluent. Concentrations of pollutants of the treated effluent are compared with standard limits to evaluate the acceptable state of the alternative. The concentrations of all pollutants in point 4, which are checked against standard limits, specify whether the treatment process of the analysed scenario in the alternative is acceptable or not. For the case of malfunction/fault of a unit, the resultant discharge of that faulty unit has no impact on declining pollutants concentration and hence the following units have to undertake treatment to reach the standard limits. The various cases of malfunction in treatment units create a set of scenarios (events) with different combinations of malfunction in units. It should be noted that reliability of each scenario needs to be analysed separately. The reliability state of these scenarios for each alternative can be identified by using event tree and fault tree analyses, which are described, in the following sections.

Here, as was mentioned, it is assumed that entered wastewater/influent into ATUs is treated by secondary treatment processes. Consequently, pollutants concentration of secondary's effluent is the same for all hybrid system alternatives and the removal efficiency of pollutants for each unit is constant. Additionally, for a better comparison, C_{1j} (effluent of secondary treatment) and discharge rate are assumed to be similar for all analysed alternatives.



Legend

C_{ij}	Influent concentration of pollutant *j* in unit *i* (mg/L)
X_{ij}	Removal efficiency of pollutant *j* related to unit *i* (%)
R_{ij}	Removed concentration of pollutant *j* by unit *i* (mg/L)
$(C_j)_{out}$	Final concentration of pollutant *j* in treated wastewater (defined as a state)

Fig. 3 Schematic mechanism of pollutant removal in a series of ATUs

2.4 Event tree analysis

Event tree analysis (ETA) is used here to calculate the reliability of each alternative. The ETA is essentially an inductive logic method to identify various sequences of events and is able to calculate the related probability of occurrence (Abdelgawad and Fayek, 2012). More specifically, Fig. 4 represents the general structure of the ETA for an alternative. This is comprised of multiple

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branches (i.e. scenarios) as a sequence of possible success/failure events for successive units. In fact, the event tree needs to enumerate all sets of possible success (i.e. unit functioning correctly) and failure (i.e. unit malfunction/faulty) states of each unit with a probability of S and F, respectively. It assumed that, each top event of a fault tree allows the evaluation of the failure state (F) which is equal to S=1-F. The computed values of S and F are conditional probability of the occurrence of an event given that events preceding that event have accrued while probability of occurrence of events is independent due to constant rate of removal efficiencies of units. It should be noted that for a series of *n* treatment units, a total of 2^n different scenarios can be envisaged. Probability of occurrence for each scenario (i.e. in a sequence) is equal to multiplication of occurrence probabilities of states (either success or failure) for all units in the sequence as shown in Fig. 4 (Zio, 2007). The secondary wastewater effluent is the initiating event assuming that always happens (i.e. probability of 100%) and thus its impact is neutralised in the occurrence probability of scenario. Thus, different states of each unit operation representing in multiple branches make up all scenarios for one alternative. The acceptable state analysis described in the previous section is carried for all scenarios to identify acceptable scenarios in each alternative. The reliability of an alternative is finally calculated by aggregating the probability of acceptable scenarios only as (Zio, 2007):

$$\text{Reliability of an alternative} = \sum \text{P(acceptable scenarios)} \tag{1}$$

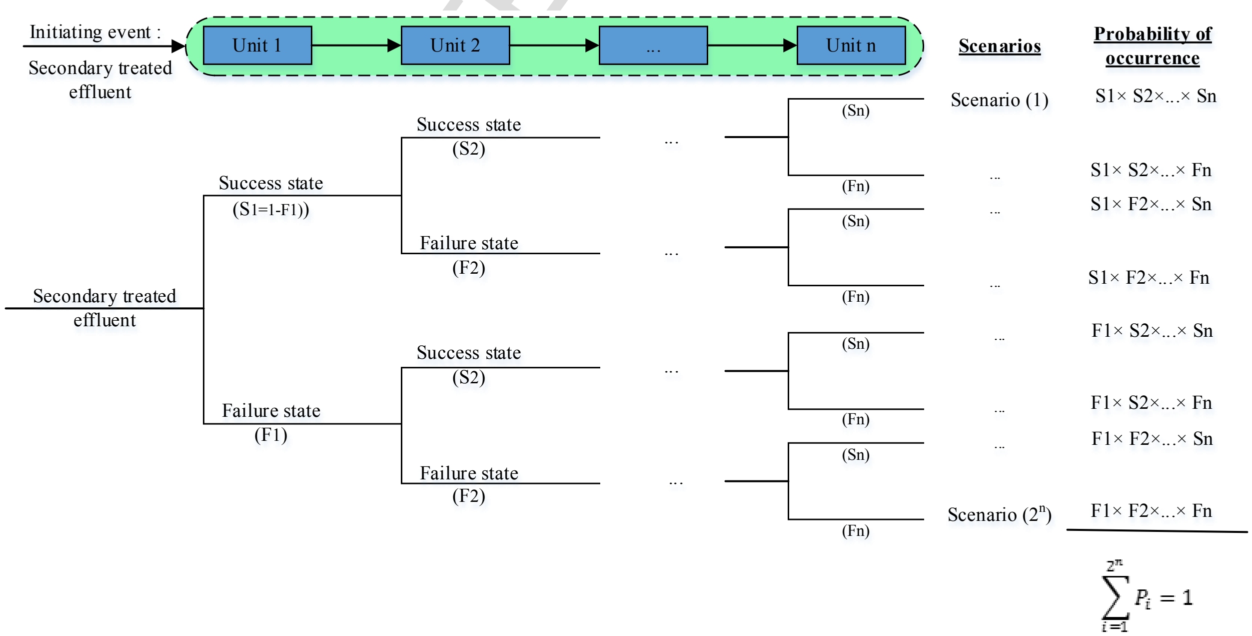

Fig. 4 Scenario-based ETA suggested for an alternative

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2.5 Fault tree analysis

Fault tree analysis (FTA) is used here to estimate the likelihood/ probability of failure (F) for each ATU, which will be then employed in ETA for reliability analysis of alternatives. More specifically, the likelihood of a top event in FTA is the failure probability of a ATU which can be considered for evaluation of the occurrence probability for that event in ETA (Zio, 2007). A typical FTA schematically shown in Fig. 5 is structured in three levels: (1) top events (TE) located in the highest level; (2) intermediate events (IE) located in the intermediate levels and (3) base events (BE) contributed in the lowest level. Events in each level is connected with related upper level events by two major logical gates of 'OR' and 'AND'. The OR gate describes the upper event will occur once one of its lower level events is occurred while the AND gate will occur only when all connected lower level events occur simultaneously (Nývlt *et al.*, 2011). Thus, the probability of occurrence (P) of an upper level event can be calculated based on probability of occurrence of connected lower level events as (Abdelgawad and Fayek, 2012):

$$\mathrm{P\ (upper\ level\ event)} = \begin{cases} 1 - \prod_{i=1}^{n} \left[1 - \mathrm{P(lower\ level\ event_i)}\right] & \text{for 'OR gate'} \\ \prod_{i=1}^{n} \mathrm{P(lower\ level\ event_i)} & \text{for 'AND gate'} \end{cases} \tag{2}$$

where n =total number of lower level events connected to the upper level event; and P =probability of occurrence. Also, note that all the events in the same level linked to one upper level event are mutually exclusive. A bottom up approach is used to calculate first the probability of occurrence for intermediate level events based on those in base events. The probability of occurrence at the top-level event is then calculated accordingly which will be used in ETA as the failure probability of ATU.

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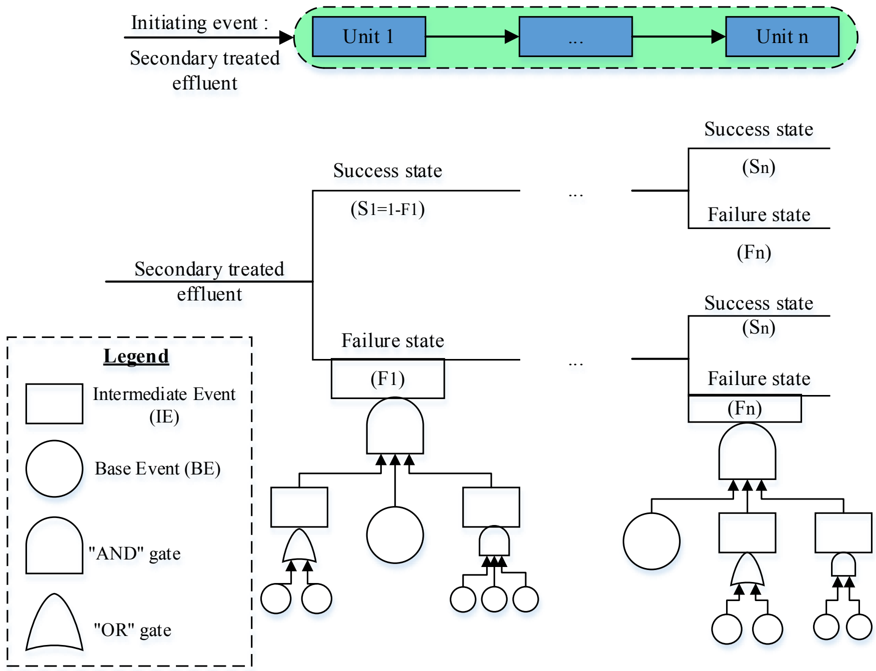

Fig. 5 Schematic fault tree analysis for evaluation of the failure probability of an event

2.5.1 Fuzzy FTA

FTA requires the performance data for the failure probability of base events (BE) in ATUs. Such data for ATUs are unlikely to be available especially in developing countries. To overcome the challenge of lack of data, the probability of occurrence of base events is determined here by experts' judgement. Both fuzzy logic and grey logic can be applied to quantify expert's judgement. However, this study uses fuzzy logic as for grey logic, there is no particular probability for values between intervals assigned to subjective judgements whereas the fuzzy logic allows the languid transition between different concepts through the use of fuzzy membership functions which depict the linguistic terms of experts describing their concepts (Abdelgawad and Fayek, 2012)

Fig. 6 represents the suggested framework of the fuzzy FTA comprising of six major steps, which are used here to calculate failure probability of each ATU. Step 1 entails defining linguistic variables and associated fuzzy membership functions for failure probability of BEs in five terms (i.e. very high (VH), high (H), medium (M), low (L), very low (VL)). The membership functions can be obtained based on experts' opinion (Rajakarunakaran *et al.* 2015).

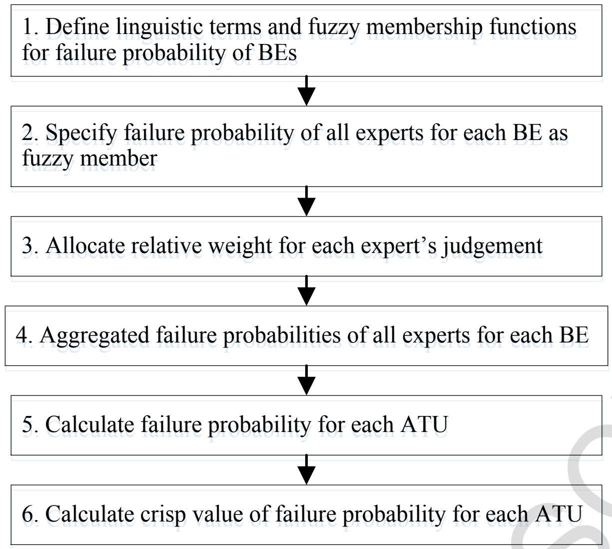

Fig. 6 Suggested framework in the fuzzy FTA

Failure probability of each BE is then specified as fuzzy membership functions in step 2. This is carried out through questionnaires or interviews with experts using linguistic terms of experts' judgements. The failure probabilities of each BE specified by the judgement of different experts need to be combined into a single failure probability by using the α–cut method in step 4 (Ahmadi *et al.*, 2016). Before this, a relative weight is also allocated for the judgement of each expert in step 3 based on the personal characteristics of the expert including job title, experience (service time) and educational level (see Table 4 in case study for instance) (Yuhuaa and Dataob, 2005). The relative weight of each expert is calculated by dividing the sum of the scores of the expert by sum of the scores of all experts.

The single fuzzy number of the failure probability of base event *i* (BE_i) aggregated for all experts is calculated by the following linear relationship:

$$P(BE)_i = \sum_{j=1}^{n} W_j * P(BE)_{ij} \tag{3}$$

where $P(BE)_{ij}$ = probability of event *i* $(BE)_i$ by expert *j* (fuzzy number); W_j =relative weight of expert *j* (real number); and *n* =number of experts. The fuzzy number of the failure probability for each ATU is then calculated according to Eq. (2) by using the α–cut method in step 5 (Ahmadi *et al.*, 2016). In the α-cut method, each fuzzy function for BEs is represented using the α-cuts. The

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α-cut of fuzzy function A is the set of all x values in the set for which the membership degree in the fuzzy function is greater than or equal to the alpha argument (Abdelgawad and Fayek, 2012). For mutually exclusive events, if probability of lower level events of a TE or IE is represented by α-cut as $[a_i,b_i]$, based on Eq. (2) and α-cut principles, the α-cut of the fuzzy probability of upper level even (a TE or IE) connected by an OR gate or by an AND gate is defined in Eq. (4):

$$\text{FP (upper level event)}^{\alpha} = \begin{cases} 1 - \prod_{i=1}^{n} [1 - a_i, 1 - b_i] & \text{for 'OR gate'} \\ \prod_{i=1}^{n} [a_i, b_i] & \text{for 'AND gate'} \end{cases} \tag{4}$$

Note that in the multiplication operator, if $A^{\alpha}=[a_1,b_1]$ and $B^{\alpha}=[a_2,b_2]$ be α-cuts for fuzzy functions of A and B, respectively, then:

$$A^{\alpha} \times B^{\alpha} = [\min(a_1a_2, a_1b_2, a_2b_1, b_1b_2), \max] \tag{5}$$

Finally, the fuzzy number related the failure probability for each ATU is converted into a crisp value (defuzzification) by using centre of gravity (COG) technique in step 6 (Ardeshir *et al.*, 2014). Steps 5 and 6 are further elaborated when the case study is described in the next section.

3 Case study description

The proposed framework is demonstrated here by its application to real case studies of hybrid ATU system of industrial wastewater in Iran. The case studies are located in semi-aired geography of Iran, where fresh water resources are very limited and sometime insufficient for meeting the water demands especially industrial demands. Therefore, industrial wastewater reuse as a clean production is a sustainable solution due to both preventing the entrance of polluted industrial wastewater to receiving water bodies and compensating the gap between water demand and supply. Industrial wastewater treatment systems for reuse purposes is currently of limited use in Iran and generally in small scale compared to total produced wastewater (ISIPO, 2016). More specifically, only about 4.1% of secondary wastewater of the total industrial effluent (6,390 out of 156,500 m^3/day) are currently treated in the industrial ATUs in Iran while it is expected that this rate increases by about 2% annually (ISIPO, 2016).

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Currently, there are 6 industrial parks equipped with hybrid ATU systems in Iran. Specifications of all these cases were used here as feasible alternatives of hybrid ATU system (Table 2). Other feasible alternatives include those suggested by relevant consultancies (approved by verified GPEX software) for future developments in other industrial parks (ISIPO, 2016). These suggested alternatives are the results of the rigorous scrutiny of potential ATU systems. All this results in 15 feasible alternatives made up of hybrid ATU systems (Table 2) that can be installed for industrial treatment in Iran (ISIPO, 2016). Each alternative representing an industrial WWTP includes a series of between 4 and 5 physical and/or chemical process units coupled with membranes. The name of existing alternatives of wastewater treatment and their location (province name in Iran) are given in Table 2. They are located in central (Semnan and Qom provices) and southern (Bushehr provice) part of Iran where fresh water resources are limited.

Table 2 Feasible alternatives of the ATUs of industrial wastewater

Alternative	Process Units					Name of industrial park / province
	Unit 1 +	Unit 2 +	Unit 3 +	Unit 4 +	Unit 5	
A1	DAF[1]	O_3[2]	MF[3]	AC[4]	RO[5]	Bushehr / Bushehr
A2	MBBR[6]	MBR[7]	AC	RO	-	SFD[13]
A3	Pre.[8]	O_3	AC	MF	RO	SFD
A4	SF[9]	AC	MF	UF[10]	RO	SFD
A5	SF	MBBR	MBR	RO	-	SFD
A6	SF	MBR	AC	RO	-	Shokuhiye / Qom AQ qala / Semnan Semnan / Semnan
A7	SF	MBR	UF	RO	-	Mobarake / Isfahan
A8	SF	MF	AC	RO	-	Murche Khurt / Isfahan
A9	SF	UF	AC	RO	-	SFD
A10	C&F[11]	O_3	AC	MF	RO	SFD
A11	SF	MBR	O_3	AC	IE[12]	SFD
A12	SF	AC	MF	UF	IE	SFD
A13	SF	UF	AC	IE	-	SFD
A14	SF	MBBR	MBR	IE	-	SFD
A15	SF	MBR	UF	IE	-	SFD

1: Dissolved air flotation 2: Ozonation 3: Micro filter 4: Activated carbon 5: Reverse osmosis
6: Moving bed biofilm reactor 7: Membrane bioreactor 8: Precipitation 9: Sand filter 10: Ultra filter
11: Coagulation and flotation 12: Ion exchange 13: Suggest for future developments

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They are made up of different combinations of 12 ATUs with the range of their removal efficiencies in Table 3 and average values (Ave) used here as X_{ij} in Fig. 3. Obviously, removal efficiency of each unit is dependent on the rate and quality of influent wastewater (design parameters) as well as position of unit in hybrid system. For this purpose, design parameters of the secondary effluent of all units are considered as a discharge rate of 300 m^3/day along with three pollutants of chemical oxygen demand (COD) of 270 mg/L, total suspended solid (TSS) of 140 mg/L and total dissolved solid (TSS) of 2300 mg/L. Due to lack of local data, the range of removal efficiencies were collected from literature reported in 36 case studies between 2007 and 2016 (see further details in appendix A). Also, note that only the last ten years of the literature was used due to fast progress of intensive improvement of treatment technologies. Although removal efficiency of an ATU may change depending on its position in the treatment chain, the average data are only considered here. Additionally, these three pollutants are used here for state control with the following limits in advanced treated effluent: COD=10 mg/L, TSS=5 mg/L and TDS=100 mg/L (Piadeh *et al.*, 2014).

Table 3 Removal efficiency of the ATUs

Unit	COD removal (%)		TSS removal (%)		TDS removal (%)	
	Range[1]	Ave	Range[1]	Ave	Range[1]	Ave
DAF	65.71-80.3	74.70	74-92	83.36	29.08-96	62.54
Per.	26.72-76.7	55.61	93.6-96	94.80	1.6	1.60
C&F	67.80-95	76.68	83-99.85	85.39	16.75-35	22.15
MBBR	57.7-96.98	77.93	85	85.00	10	10.00
MBR	87.7-99.9	94.61	97.84-99.8	99.03	7.34-18.3	9.15
O_3	55-89	69.75	18-23.5	20.99	18	18.00
SF	32.08-94	68.36	58.33-90	74.84	25-31	28.00
MF	71.43-95.42	81.01	81-99	88.89	1-3.25	1.56
UF	56.46-99.2	82.43	94.14-100	81.16	0.3-3.71	1.95
AC	62.32-97.4	84.19	72.73-97.59	85.16	0.79-22.3	11.55
IE	51.76-93.4	75.68	97.1-99.85	99	97.7-99.53	98.68
RO	77.99-98	91.04	94.12-98.5	97.03	87.54-98.18	94.45

[1] The range of removal efficiency reported in the literatures (See Table A.1 in Appendix A)

The fault tree used here for FTA of each ATU is constructed based on the interview with a number of experts. Base of the interview, fault trees for all units are constructed similarly as shown in Fig. 7 comprising 9 intermediate events, 21 base events with the details given in Table 4.

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According to the conducted fault tree, the ATU failure can be due to five main causes including (1) undesired secondary effluent; (2) Failure of pipes and joints; (3) failure of energy sources; (4) failure of equipment and (5) failure of valves and gates. The event of undesired influent to ATUs can be linked to water quality and overflow issues in base events. Other ATU failures can be originated from infrastructure problems related to its design, construction, operation and maintenance.

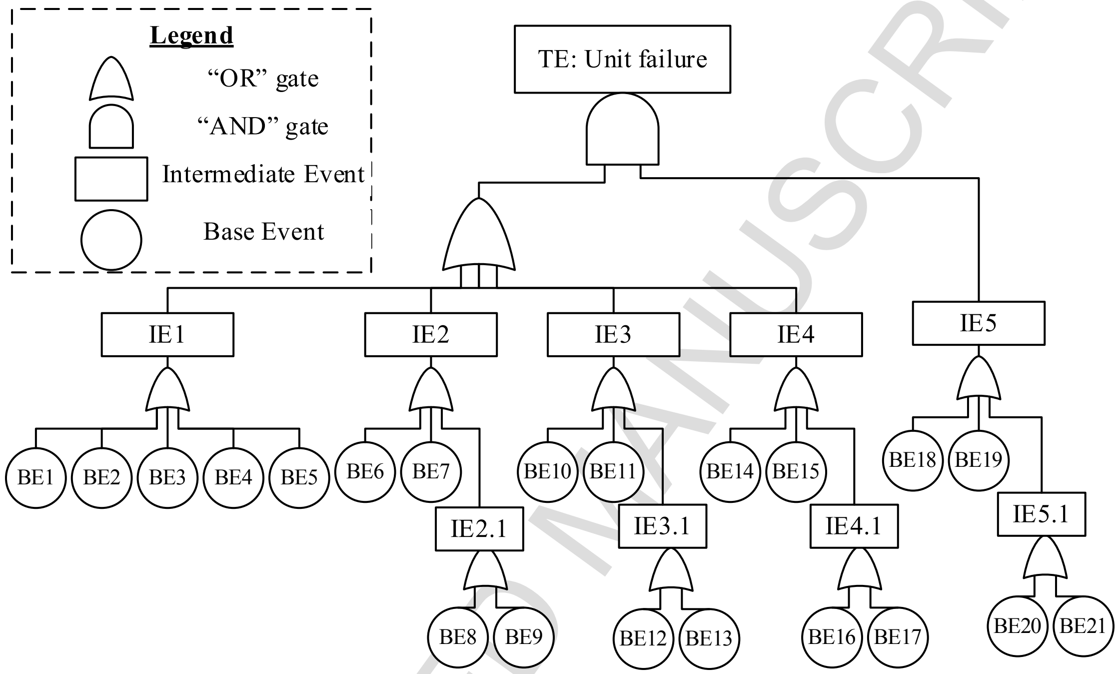

Fig. 7 Structure of FTA of ATUs in the case study

According to the constructed fault tree in Fig. 7, the ATU failure (i.e. top event) can be summarised to combination of base events by using of Boolean algebra and considering OR ($\cup$) and AND ($\cap$) gates as:

$$TE = (IE1 \cup IE2 \cup IE3 \cup IE4) \cap IE5 = (\bigcup_{i=1}^{17} BEi) \bigcap (\bigcup_{i=18}^{21} BEi) \quad (5)$$

By considering Eq. (2), the fuzzy probability (FP) of ATU's failure (TE) can be calculated based on the fuzzy probability of base events' failure by using α–cut method as:

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$$FP(TE) = (1 - \prod_{i=1}^{17}(1 - FP(BE_i))) * (1 - \prod_{i=18}^{21}(1 - FP(BE_j))) \quad (6)$$

Table 4 Fault tree events of failure in the ATUs of the case study

Code	Name	Description
TE	**Failure of a ATU**	-
IE1	**Undesired secondary effluent**	Entering secondary effluent with excessive undesired water quality into the ATU
BE1	Excessive COD	Entering secondary effluent with excessive concentration of COD
BE2	Excessive TSS	Entering secondary effluent with excessive concentration of TSS
BE3	Excessive TDS	Entering secondary effluent with excessive concentration of TDS
BE4	Improper pH	Entering secondary effluent with undesired pH (below the 7 or over 9)
BE5	Excessive Q	Entering excessive flow of secondary effluent
IE2	**Failure of pipes and joints**	Any problems in pipes and joints such as burst, leakage, breakage and blockage
BE6	Incorrect design	Improper design by the consultant
BE7	Incorrect construction	Improper construction or equipment by the contractor
IE2.1	Incorrect maintenance	Improper maintenance by the operator
BE8	Inappropriate maintenance	insufficient maintenance and inspection
BE9	Inefficient rehabilitation	Lack of timely replacement of equipment
IE3	**Failure of energy sources**	Any problems in pumps, power supply, generators
BE10	Incorrect design	Improper design by the consultant
BE11	Incorrect construction	Improper construction or equipment by the contractor
IE3.1	Incorrect maintenance	Improper maintenance by the operator
BE12	Inappropriate maintenance	insufficient maintenance and inspection
BE13	Inefficient rehabilitation	Lack of timely replacement of equipment
IE4	**Failure of equipment**	Any problem in accessories and equipment of the ATU
BE14	Incorrect design	Improper design by the consultant
BE15	Incorrect construction	Improper construction or equipment by the contractor
IE4.1	Incorrect maintenance	Improper maintenance by the operator
BE16	Incorrect maintenance	Insufficient maintenance and inspection

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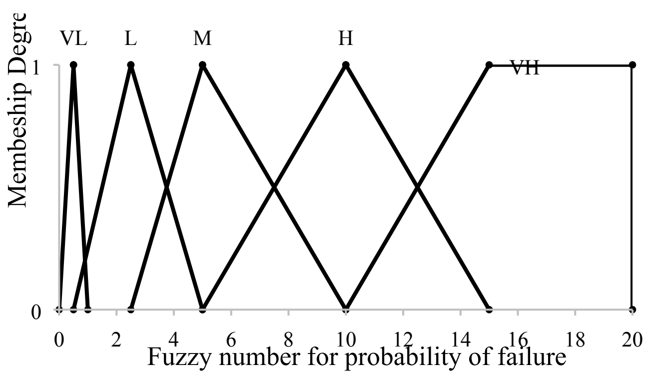
Code	Name	Description
BE17	Inappropriate maintenance	Lack of timely replacement of equipment
IE5	**Failure of valves and gates**	Any problem in control valves and gate
BE18	Incorrect design	Improper design by the consultant
BE19	Incorrect construction	Improper construction or equipment by the contractor
IE5.1	Incorrect maintenance	Improper maintenance by the operator
BE20	Inappropriate maintenance	insufficient maintenance and inspection
BE21	Inefficient rehabilitation	Lack of timely replacement of equipment

By constructing fault tree, linguistic terms and associated fuzzy membership functions for failure probability of BEs are defined based on experts' opinion as shown in Fig. 8. Note that, in experts' opinion in this case, the failure probability of BEs is limited to 20.



Linguistic Term	Trapezoidal presentation			
	a^*	b^*	c^*	d^*
Very Low (VL)	0	0.5	0.5	1
Low (L)	0.5	2.5	2.5	5
Medium (M)	2.5	5	5	10
High (H)	5	10	10	15
Very High (VH)	10	15	20	20

* a, b, c and d are boundaries of membership functions

Fig. 8 Linguistic terms and fuzzy membership functions used for failure probability of base events

To combine different experts' judgements on each BE into a single failure probability by using of experts' relative weight, a scoring system is proposed based on the characteristics of experts including job title, experience (service time) and educational level as shown in Table 5. The relative characteristics used in the Table are based on the suggestions made by Yuhuaa and Dataob (2005) and scores are obtained by experts' judgments.

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Table 5 Scores of experts' characteristics

Expert's characteristics	Score
Job title (Range: 1-3):	
• Ministry of industry *:	
- Manager in central organisation	2
- Manager in state organisation	1
• Consultant:	
- Manager	3
- Designer	1
• Contractor:	
- Manager	3
- Field operator**	1
• Operators***:	2
Educational level (1-3):	
- Diploma or lower	1
- B.Sc.	2
- M.Sc.	2.5
- Ph.D.	3
Service time (1-2):	
<5 years	1
>5 years	2

* Responsible for providing the financial budget, and supervision during the operation

**Responsible for constructing and also 1-year operating system as a temporary delivery

***Hired by board of trustees for operating the system

4 Results and discussion

The methodology is applied here for reliability assessment of 15 feasible alternatives of ATU systems proposed for industrial parks in Iran. The fuzzy FTA is first developed and analysed for ATUs based on experts' judgements. More specifically, the failure probabilities for each of 12 ATUs are determined separately by using the linguistic terms defined by experts. A total of 15 related experts consisting of governmental managers, consultants, contractors, and operators contributed to the questionnaire to evaluate and specify the failure probabilities of base events for each ATU. For example, the linguistic terms of failure probabilities of 21 base events specified by 15 experts and their relative weights (steps 2 and 3 in Fig. 6) for activated Carbon unit only are illustrated in Table 5. This table also shows the single aggregated fuzzy number of failure probabilities first for each base event (step 4 in Fig. 6) using Eq. (3) and finally for top event (step 5 in Fig. 6) using Eq. (6) for this ATU as a result of the fuzzy FTA. Corresponding tables for other ATUs are also developed similarly.

Fig. 9 shows the fuzzy numbers of failure probability for all 12 ATUs obtained from FTA as described in Table 6 and the α-cut method. The crisp values of failure probabilities of ATUs obtained by defuzzification are also shown (P*) in the figure (step 6 in Fig. 6). As can be seen, RO, O_3 and IE units face the highest failure probability with 30%, 24% and 22%, respectively, while C&F has the lowest failure probability (5.4%). The relative rates of the failure probability rates calculated in the figure were approximately confirmed by the experts who participated in the questionnaire. Akhoundi and Nazif (2018) showed that RO unit can have considerable negative effect on reliability of hybrid systems. This can verify the highest failure probability of RO obtained in this study. As previously reviewed in the literature review, prior researches about the reliability of ATUs are limited as reliability assessment was more investigated for secondary treatment units. However, those who evaluated reliability in ATUs reported reliability for MBR system between 30% (Arroyo and Molinos-Senante, 2018) and 100% (Kalbar *et al.*, 2012) which can be related to special conditions of those case studies (e.g. age of unit, influent quality, manufacturing of MBR and etc.). Comparing the reliability of ATUs obtained in this study with those in literature show that MBR obtained in this study (82.38%) is close to Kalber *et al.* (2012) although their reliability (i.e. 100%) is too optimistic and hence cannot be realistic.

According to the experts' judgements, the high rate of failure probability in RO and O_3 can be attributed to the high failure probability of base events related to equipment (IE4) and valves and gates (IE5). Therefore, in order to reduce the failure probability of these units, the failure rates of the base events related to these intermediate events should be reduced.

26 **Table 6 Linguistic terms and integrated fuzzy numbers of failure probability for base events of Activated Carbon unit in FTA**

No of base event	Number of experts															FP(BE)*	FP(TE)**
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		
	Relative weight of expert																
	0.0692	0.0755	0.0755	0.0629	0.0566	0.0692	0.0881	0.0440	0.0629	0.0629	0.0629	0.0629	0.0629	0.0818	0.0629		
	Expert's judgment																
1	L	L	M	M	L	M	L	M	M	L	M	L	M	L	H	(1.66,4.07,4.07,7.83)	(3.55,12.22,12.98,26.51)
2	L	L	M	H	M	L	L	L	VL	H	VL	L	M	L	M	(1.52,3.84,3.84,7.04)	
3	L	M	L	M	L	VL	M	M	M	L	L	L	M	VH	L	(2.03,4.37,4.78,7.93)	
4	VH	L	L	VH	H	M	VH	H	M	H	L	VL	M	H	M	(4.18,7.61,8.71,11.79)	
5	M	VL	L	L	H	VL	L	L	L	M	M	L	M	L	L	(1.20,3.28,3.28,6.27)	
6	M	M	M	L	L	VL	L	H	M	H	H	VH	H	H	M	(3.17,6.37,6.69,10.54)	
7	M	H	M	L	VH	VL	M	L	M	L	L	H	VH	H	H	(3.47,6.71,7.31,10.82)	
8	H	H	H	H	H	L	M	M	M	VH	H	H	L	VL	H	(3.82,7.57,7.89,11.87)	
9	M	M	L	H	L	VL	L	VH	H	L	M	M	M	M	M	(2.41,5.05,5.27,9.03)	
10	M	L	M	VL	H	M	L	H	H	M	H	VH	M	H	H	(3.49,6.79,7.10,11.10)	
11	M	M	H	H	H	M	M	L	H	L	L	L	VL	L	H	(2.51,5.53,5.53,9.46)	
12	M	M	L	L	M	H	H	VL	L	VH	L	H	H	H	M	(3.25,6.59,6.90,10.73)	
13	M	M	M	M	M	H	H	M	L	H	VL	VL	M	L	L	(2.32,5.02,5.02,8.93)	
14	H	L	M	VL	M	L	H	M	M	M	L	H	L	M	L	(2.22,4.98,4.98,8.87)	
15	H	M	M	L	M	H	VL	VH	L	M	M	M	H	L	M	(2.69,5.53,5.75,9.61)	

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16	H	M	L	H	M	M	L	H	L	H	L	L	H	H	M	(2.75,6.04,6.04,10.16)
17	M	L	M	H	H	M	VL	M	L	L	L	L	L	M	L	(1.67,4.07,4.07,7.54)
18	M	L	L	VL	VL	H	H	H	M	M	M	L	L	L	M	(1.99,4.57,4.57,8.14)
19	M	M	M	M	L	L	H	VH	H	M	L	M	L	M	M	(2.70,5.56,5.79,9.94)
20	H	M	M	VH	M	H	M	L	L	L	M	M	VH	L	L	(3.16,6.16,6.79,10.38)
21	M	L	M	M	L	M	H	L	M	M	L	VL	H	H	L	(2.32,5.13,5.13,9.09)

FP(BE): fuzzy probability of base event FP(TE): fuzzy probability of top event

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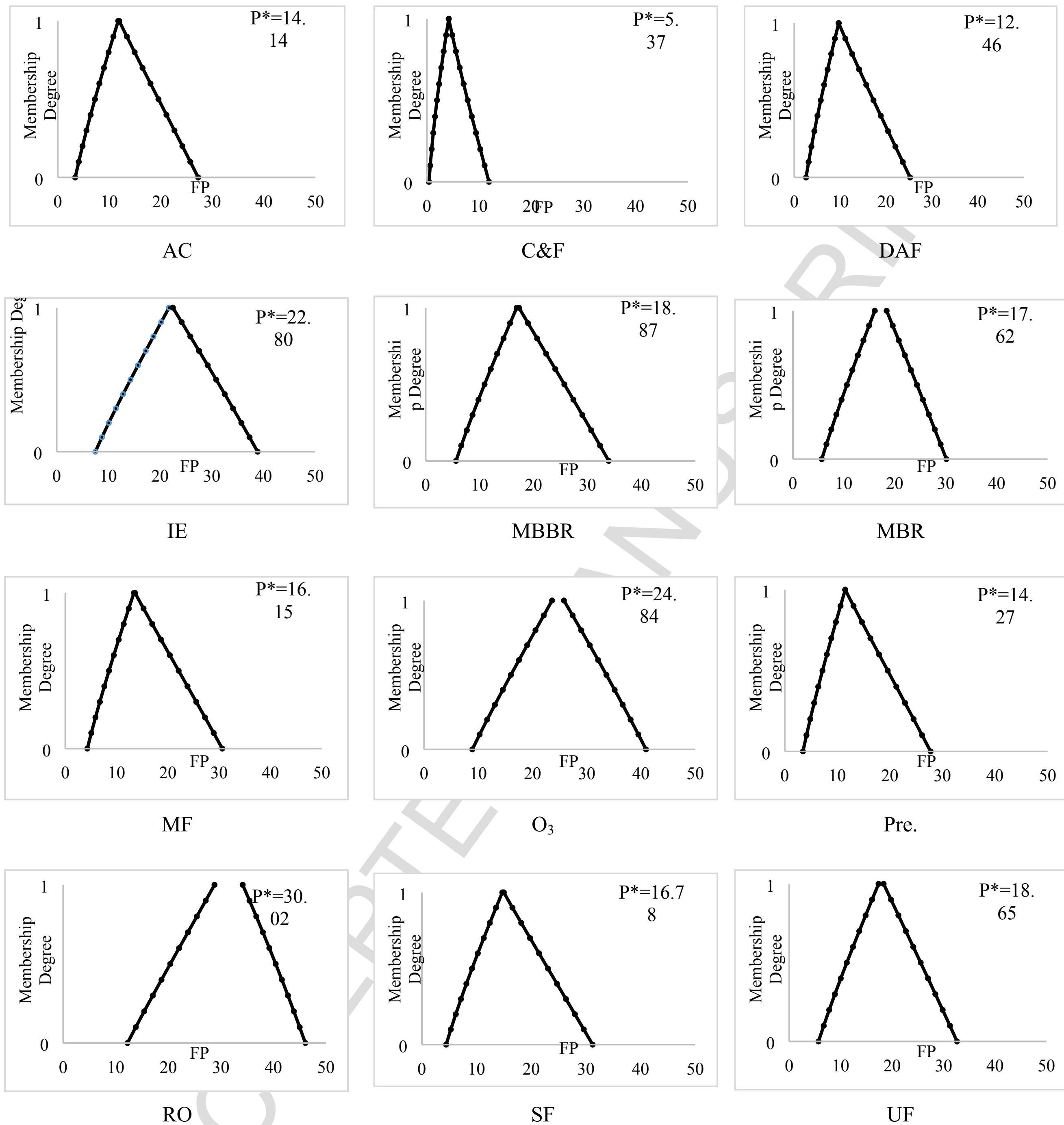

Fig. 9 Fuzzy number of failure probability for the analysed ATUs

By obtaining failure probability of each ATU as a crisp number, the reliability assessment of each alternative is undertaken by ETA. This entails first specifying all scenarios and then identifying scenarios in accordance with the state analysis defined earlier for water quantity of the treated effluence. For example, this procedure is illustrated in Table 7 for alternative A2 consisting of four ATUs (MBBR, MBR, AC and RO in sequence). As can be seen, out of 16 scenarios, only 6 could satisfy all water quality requirements. This is mainly due to the violation of TDS since RO as the main contributor to TDS removal fails. After TDS, violations of TSS and COD are in most cases because of the failure in RO. It can be concluded that the RO functioning is vital for the operation of this alternative. Finally, the reliability of the alternative can be obtained by using Eq. (1) equal to 68.11% based on probabilities of acceptable scenarios. The value is mainly due to the high rate of scenario 1 (40%) which is the multiplication of success states in all units with high success probability rates. Similarly, a large proportion of overall reliability in other alternatives is dependent on success probability rates of all the units constituting those alternatives.

Reliability of other alternatives can be calculated similar to Table 7. Finally, ranking of 15 analysed alternatives based on the reliability indicator is summarized in Table 8. The ranking indicates that alternatives of A12 (SF+AC+MF+UF+IE), A11 (SF+MBR+O3+AC+IE), and A10 (C&F+O3+AC+MF+RO) are the most reliable hybrid ATU systems with 74.82%, 74.79%, and 70.01%, respectively. The performance of reliability for the 3 top ranking alternatives (A12, A11 and A10) is schematically illustrated in Fig 10 along with related units and their success probabilities. Although the average of individual units (S_{ave}) is relatively similar from the highest to the lowest alternative, the changes of reliability values within this range is rather sensible. Moreover, it can be concluded that the alternatives with higher success probability rate in separate units (i.e. S_{ave}) cannot necessarily result in a better reliability. For example, the reliability of A11 is higher than A10 (74.8% compared to 70.0%) while S_{ave} of A10 is higher than A11. In addition, no specific relationship can be found between the highly ranked alternatives and specific individual units. This can also verify the paramount importance of the suggested reliability assessment methodology which needs to be conducted for the hybrid ATU systems. Moreover, the ranking shows that the five top ranked alternatives contain 5 units whereas alternatives with 4 units rank in the following. Although no strict correlation is observed between the number of units and higher reliability, this can indicate that alternatives with 5 units are likely to be ranked higher than those with 4 units.

Table 7 Reliability assessment of alternative A2 (MBBR+MBR+AC+RO)

No of scenario	Advanced Treatment Units								Effluent quality (mg/L)[3]			State of Scenario	P(Scenario) (%)	Reliability (%)
	MBBR		MBR		AC		RO							
	State	Probability	State	Probability	State	Probability	State	Probability	COD	TSS	TDS			
1	S[1]	0.81	S	0.82	S	0.86	S	0.70	<1	<1	92.3	✓[4]	39.98	
2	S	0.81	S	0.82	S	0.86	F	0.30	<1	<1	**1663.5**	×[5]	17.14	
3	S	0.81	S	0.82	F	0.14	S	0.70	<1	<1	99.8	✓	6.51	
4	S	0.81	S	0.82	F	0.14	F	0.30	3.2	<1	**1880.6**	×	2.79	
5	S	0.81	F	0.18	S	0.86	S	0.70	3.8	<1	97.8	✓	8.78	
6	S	0.81	F	0.18	S	0.86	F	0.30	9.4	**10.8**	**1831.3**	×	3.76	
7	S	0.81	F	0.18	F	0.14	S	0.70	5.3	<1	98.8	✓	1.43	
8	S	0.81	F	0.18	F	0.14	F	0.30	**59.6**	**21**	**2070**	×	0.61	68.11
9	F[2]	0.19	S	0.82	S	0.86	S	0.70	<1	<1	102.6	✓	9.38	
10	F	0.19	S	0.82	S	0.86	F	0.30	2.3	<1	**1848.3**	×	4.02	
11	F	0.19	S	0.82	F	0.14	S	0.70	1.3	<1	**115.9**	×	1.53	
12	F	0.19	S	0.82	F	0.14	F	0.30	**14.5**	1.4	**2089.6**	×	0.65	
13	F	0.19	F	0.18	S	0.86	S	0.70	3.9	2.1	97.3	✓	2.06	
14	F	0.19	F	0.18	S	0.86	F	0.30	**42.7**	**72**	**2034.5**	×	0.88	
15	F	0.19	F	0.18	F	0.14	S	0.70	**24.2**	4.2	**127.7**	×	0.34	
16	F	0.19	F	0.18	F	0.14	F	0.30	**270**	**140**	**2300**	×	0.14	

[1] S: Success state

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[2] F: Failure state

[3] Those values violated the limits are highlighted in bold

[4] ✓: Acceptable scenario as all three water quality parameters are within the allowable ranges of the effluent quality.

[5] ✗: Unacceptable scenario as at least one of the three water quality parameters exceeds its allowable range of the effluent quality.

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Table 8 Ranking of alternatives based on reliability

Rank	Alternative No	Combination of alternative	Reliability (%)	S_{ave} (%)
1	A12	SF+AC+MF+UF+IE	74.82	82.30
2	A11	SF+MBR+O3+AC+IE	74.79	80.76
3	A10	C&F+O3+AC+MF+RO	70.01	81.90
4	A1	DAF+O3+MF+AC+RO	68.42	80.48
5	A6	SF+MBR+O3+AC+RO	69.56	79.32
6	A9	SF+UF+AC+RO	68.32	80.10
7	A4	SF+AC+MF+UF+RO	68.32	80.85
8	A8	SF+MF+AC+RO	68.32	80.73
9	A2	MBBR+MBR+AC+RO	68.11	81.04
11	A5	SF+MBBR+MBR+RO	67.75	79.18
10	A3	Pre. + O3+AC+MF+RO	67.52	80.12
12	A7	SF+MBR+UF+RO	66.10	79.23
13	A14	SF+MBBR+MBR+IE	63.60	80.98
14	A15	SF+MBR+UF+IE	63.60	81.04
15	A13	SF+UF+AC+IE	53.92	81.91

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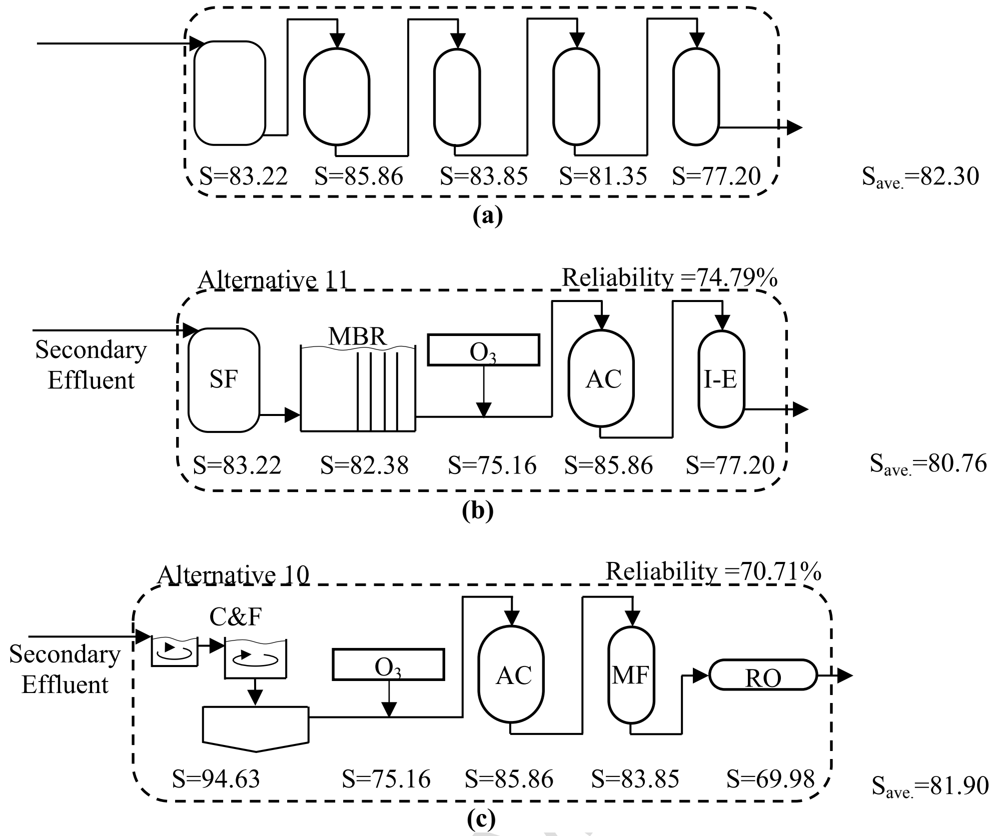

Fig. 10 Schematic process of Prioritised alternatives and their reliabilities: a) Alternative 12, b) Alternative 11, c) Alternative 10; note that S indicates the success probability of a unit

Table 9 compares the ranking of alternatives with the relevant ranking for each removal efficiencies of alternatives when all units of an alternative work properly. As shown in the table, although A2 has the best removal efficiency in COD and TSS, it is ranked ninth based on reliability of alternatives. Similarly, A11 with highest rank for TSS and TDS removal, the reliability rank of the alternative is second. It implies that reliability-based ranking in ATU alternatives can be independent from the performance of individual removal efficiencies even with high performance for one or two parameters in an alternative.

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Table 9 Comparison of ranking of alternatives based on reliability vs removal efficiency

Rank based on reliability	Alternative No	Removal efficiency and ranks when all units work properly					
		COD		TSS		TDS	
		% Removal	Rank	% Removal	Rank	% Removal	Rank
1	A12	99.03	11	100	1	99.19	3
2	A11	99.67	9	100	1	99.37	1
3	A10	99.70	1	99.98	10	96.91	7
4	A1	99.86	3	99.98	10	98.52	6
5	A6	99.82	3	99.98	10	98.52	6
6	A9	99.98	11	99.89	15	96.53	10
7	A4	99.94	3	99.99	8	96.59	9
8	A8	99.94	10	99.94	14	96.52	11
9	A2	99.82	1	100	1	95.99	14
10	A5	99.98	7	100	1	96.73	8
11	A3	99.91	6	99.99	8	96.1	13
12	A7	99.97	7	100	1	96.44	12
13	A14	99.97	13	100	1	99.22	2
14	A15	99.95	14	100	1	99.15	5
15	A13	99.97	15	99.96	13	99.18	4

Table 10 shows the rate of acceptable scenarios for alternatives in ETA, which can be compared with the reliability-based ranking of alternatives. As shown in the table, higher rate of acceptable scenarios cannot necessarily lead to better rank based on reliability. For example, the effluent quality for 87.5% of total scenarios in alternative A6 is acceptable (i.e. within the allowable limits) but reliability-based rank of this alternative is fifth. This can be linked to the failure probability of acceptable scenarios, which is lower in alternatives with higher reliability-based ranks.

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Table 10 Rate of acceptable scenarios of alternatives in ETA

Rank based on reliability	Alternative No	Number of acceptable scenarios	Total number of scenarios	% success
1	A12	10	32	31.25
2	A11	11	32	34.38
3	A10	10	32	31.25
4	A1	18	32	43.75
5	A6	14	16	87.50
6	A9	10	16	37.50
7	A4	20	32	37.50
8	A8	10	16	37.50
9	A2	10	16	37.50
10	A5	10	16	37.50
11	A3	20	32	37.50
12	A7	5	16	31.25
13	A14	12	16	25.00
14	A15	12	16	25.00
15	A13	14	16	12.50

Fig. 11 also shows the percentage of unacceptable scenarios with respect to each water quality parameters of effluent. As shown in the figure, violation of TDS limit is the major reason for unacceptance of scenarios in most of alternatives except the last three alternatives (A13-A15) in which COD limit is the major reason for unaccepting scenarios. Therefore, TDS removal efficiency can be considered as a key factor when designing a new ATU system which can effectively have impact on achieving a larger rate of acceptable scenarios and hence reliability of the system.

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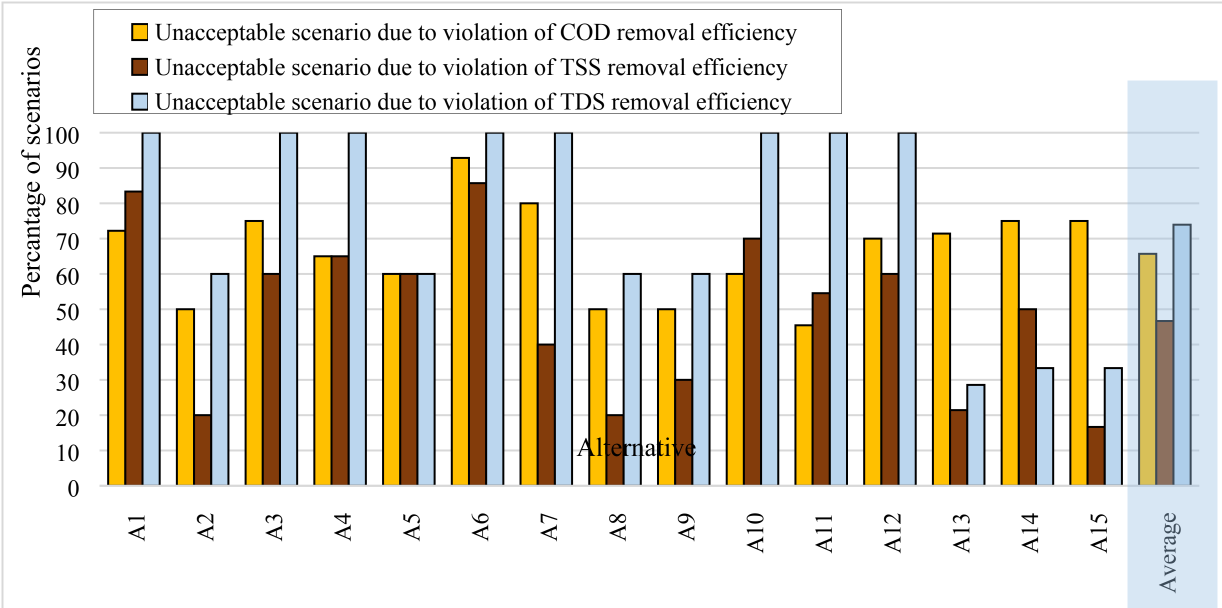

Fig. 11 Percentage of unacceptable scenarios with respect to water quality parameters of effluent

5 Conclusions

This paper presented a new methodological framework to investigate the potential of combined fuzzy FTA and ETA for reliability assessment and prioritisation of hybrid system alternatives in advanced treatment units of industrial wastewater. The methodology was specifically demonstrated on a real case study in a developing countries with poor data and experience available for these hybrid systems. The framework employed a combined analysis of event tree and fuzzy fault tree to identify failure probability of advanced treatment processes in series. More specifically, FTA was structured as a fault tree representing main causes of ATU failure in three levels of top, intermediate and base events. Failure probability of base events were obtained by using fuzzy logic and linguistic terms of a number of experts' judgements expressing the main causes of ATU failures in the case study. Then, ETA was used to calculate a reliability of each hybrid system alternative. This was achieved through a statistical analysis for success scenarios (i.e. concentration of pollutants in effluent of the hybrid system falls within standard limits) of failure events (i.e. once one or more ATUs fails in the hybrid system). The feasible alternatives of hybrid ATU systems were finally ranked based on the calculated reliability. Based on the results obtained in the case study, the following conclusions are drawn:

- The suggested methodology and framework provided a standard platform for failure assessment of both individual ATUs and hybrid ATU systems where historic data collection and experience for such treatment systems is a major obstacle. This is particularly important for new developments of industrial wastewater treatment with no or little previous experience of these systems and minimises the failure risk of capital investment.
- This framework is a useful tool for failure risk assessment and prioritisation of various combinations of ATUs and selecting the best combination of advanced treatment units with highest reliability.
- The failure probability of each ATU is individually determined based on fuzzy FTA based on the linguistic judgements of a number of experts on the main causes of ATU failure. The failure probabilities of individual ATUs is then used by ETA to determine reliability of feasible hybrid system alternatives in the case study analysed here. The failure probabilities obtained here are valuable data for reliability assessment of any other potential combination of ATUs at the national scale.
- The results in the paper show no correlation between the average of success probability of individual ATUs in a hybrid system and the overall reliability of the system. Therefore, a higher average removal efficiency for the individual ATUs cannot necessarily lead to a more reliable hybrid system.
- In addition to feasible hybrid systems tested/suggested in the case study, the analyses of failure probability in this study can be used to create some hybrid systems with high reliability. On the other hand, the feasible hybrid ATU systems with low reliability evaluated by this methodology can be analysed later on for improvement of main causes of ATU failure by focusing on the base events with highest failure.

The failure probability of individual ATUs in this study were obtained based on the linguistic judgements of different experts on the failure rate those ATUs. Although the accumulation of experts' judgements is based on a weighted average with respect to the experience of experts, this can only be applied to specific manufacturing of the analysed ATUs. If a new manufacturing for a ATU with different quality and performance is intended to be used in a hybrid system, the judgments of experts used in this study cannot be applied for reliability assessment of the same hybrid systems. In addition, using the failure probability of ATUs obtained in this study cannot be directly used for similar systems elsewhere in the world due mainly to different features and performance of individual ATUs. However, the framework suggested in this paper can be applied similarly. As the results obtained in this methodology are based on experts' judgments, further sensitivity analysis needs to be conducted especially on ATUs and their base events with high failure probability before they can be recommended to decision makers. In addition to the reliability assessment of hybrid ATU systems, its correlation with other performance indicators (e.g. overall removal efficiency, cost-effectiveness and etc.) should also be analysed to make a multi criteria decision based on sustainability.

Acknowledgement

Authors would thank to all staff and managers of Iran small industries and industrial parks organization, Pars Ariyan consulting company, Water and wastewater research consulting company and Faraz Ab consulting company for their honestly cooperation to complete required data.

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278 ## Appendix A:

279 **Table A.1 Estimation of removal efficiency in advanced treatment units of industrial wastewater treatment in**
280 **the literatures**

Advanced treatment unit	Removal efficiency of pollutants	Reference
RO	98.18 TDS	Nandy *et al.* 2007
UF	83.33% COD / 2% TDS	Nandy *et al.* 2007
C&F	95% COD / 85% TSS	Amuda and Amoo 2007
MBR	95.52% COD / 99% TSS	Tam *et al.* 2007
MF	95.42% COD / 99% TSS / 93.63% TDS	Tam *et al.* 2007
RO	88.57% COD / 87.54% TDS	Tam *et al.* 2007
Per.	26.75% COD / 96% TSS / 1.6% TDS	Solmaz *et al.* 2007
C&F	83% TSS / 17% TDS	Üstünm *et al.* 2007
IE	51.76% COD / 99% TSS / 98.68% TDS	Üstünm *et al.* 2007
RO	95% COD	Vourch *et al.* 2008
C&F	91% COD / 99.4% TSS	Ahmad *et al.* 2012
UF	95% COD	Zirehpour *et al.* 2008
DAF	77% COD / 74% TSS	De Nardi *et al.* 2008
DAF	72% COD / 92% TSS	Al-Mutairi *et al.* 2008
MBR	93.74% COD	Hoinkis and Panten 2008
O_3	71% COD	Germirli Babuna *et al.* 2009
O_3	70% COD	Preethi *et al.* 2009
MBR	95.2% COD / 99.8% TSS	Takht Ravanchi *et al.* 2009
SF	79% COD / 90% TSS	Achak 2009
DAF	80.3% COD / 75.5% TSS	De Sena *et al.* 2009
AC	76.74% COD / 97.59% TSS	Ciabattia *et al.* 2009
RO	98% COD	Madaeni and Eslamifard 2010
O_3	55% COD	Tehrani-Bagha *et al.* 2010
C&F	72.5% COD	Aber *et al.* 2010
MBR	91.97% COD / 99.47% TSS / 18.3% TDS	Brannock *et al.* 2010
DAF	77.5% COD / 88.7% TSS	El-Gohary *et al.* 2010
Per.	76.7% COD / 93.6% TSS	El-Gohary *et al.* 2010
RO	93.6% COD / 97.5% TSS / 95.1% TDS	Huang *et al.* 2011
UF	66.9% COD / 95.8 TSS / 1.8% TDS	Huang *et al.* 2011

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Advanced treatment unit	Removal efficiency of pollutants	Reference
C&F	75% COD / 98% TSS / 17% TDS	Ayoub *et al.* 2011
MF	86.67% TSS	Ordóñez *et al.* 2011
C&F	60% COD / 94% TSS	Ayeche 2012
MBR	99.9% COD	López-Fernández *et al.* 2012
RO	93.3% COD	Kurt *et al.* 2012
MBR	96.19% COD / 97.84% TSS	Malamis *et al.* 2012
RO	80.95% COD / 96.85% TDS	Chowdhury *et al.* 2013
O_3	89% COD / 18% TDS	Ferella *et al.* 2013
SF	94% COD / 31% TDS	Ferella *et al.* 2013
MBR	87.7% COD	Chung and Kim 2013
MBR	96.98% COD	Lei *et al.* 2010
MBBR	96.98% MBBR	Lei *et al.* 2010
MBR	97.9% COD	Andrade *et al.* 2014
UF	22% COD / 89.97% COD	Petrinic *et al.* 2015
RO	99.99% COD / 99.97% TSS	Petrinic *et al.* 2015
MBR	55.65% COD / 8.17% TDS	Yao *et al.* 2016

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Highlights

- Reliability of hybrid advanced treatment unit (ATU) system is evaluated
- Hybrid ATU system is comprised of ATUs of industrial wastewater treatment
- New framework for reliability assessment of hybrid ATU system is proposed
- Reliability assessment is calculated by event tree and fault tree analyses
- 15 hybrid ATU system alternatives is ranked based on Reliability assessment.

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